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LIGHTERAGE SEASICKNESS
PARAMETRIC STUDY

by

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This report summarizes the results of a study performed to estimate seasickness corresponding to several different proposed configurations associated with the Joint Modular Lighterage System (JMLS). Specifically, the dynamic behavior of different modular barges with a heavy load was modeled in a variety of sea state 3 environments. This study consisted of identifying a single representative wave spectrum, running the SCORES vessel dynamics computer model for a variety of conditions (barge size, wave direction and water depth), and comparing the RMS vertical accelerations at various points on the barge deck. A literature survey was completed regarding seasickness criteria, which was then used to convert the RMS accelerations into seasickness potential for varying positions on the vessel.

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LIGHTERAGE SEASICKNESS PARAMETRIC STUDY

Abstract

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Barge Description

The JMLS barge is modular, with each module being 40-ft long by 24-ft wide by 8-ft deep. This analysis modeled 80-ft, 120-ft and 160-ft long (i.e., 2, 3, and 4) multiple-module configurations. Each module was assumed to carry one Abrams battle tank weighing 70 tons centered on the deck. In addition, one double width (48-ft) and one lower freeboard (7-ft) module configuration were analyzed. A nominal water depth of 100-ft was used for all configurations. However, an additional 12-ft water depth was tested for the 120-ft by 24-ft by 8-ft configuration.

Vessel Dynamics Analysis

The analysis was performed on the SUN Unix computers in the Ocean Engineering Division using the aforementioned barge configurations. The barges were subjected to a Bretschneider wave spectrum corresponding to sea state 3 (significant wave height = 4.6-ft; mean wave period = 4.6 seconds) with the waves approaching the barge at angles of 0, 22.5, 45, 67.5 and 90°. Root Mean Square (RMS) accelerations at 4 key points on the barge deck were sought (see Figure 1):

> 1 - the center of the bow
>
> 2 - the starboard corner of the bow
>
> 3 - the absolute center of the barge
>
> 4 - the starboard edge at the midpoint of the barge.

A widely-available conventional linear strip theory model named SCORES (Reference 1) was used to calculate the vessel dynamics in waves. SCORES calculates motions in the frequency domain using response amplitude operators (RAOs). There are 6 RAO functions of frequency for the response of the six rigid body degrees of freedom due to a unit amplitude wave (RAOs are numbered 1 through 6, corresponding to surge, sway,

1

heave displacements of the center of gravity, and roll, yaw, and pitch rotations, respectively). The component barge response in the jth degree of freedom is found at each frequency by assuming small rotation, linear motions according to Equation (1):

$$Y_j(f_i)=RAO_j(f_i)*W(f_i) \qquad (1)$$

All variables in Equation (1) are complex, and the discrete frequency (f_i) is defined using a uniform distribution over the frequency axis ($f_i=i \Delta f$). $W(f_i)$ is the Fourier Transform of the wave amplitude and $Y_j(f_i)$ is the Fourier Transform of the jth response mode (e.g., surge). The complex representation maintains phase (sine and cosine vectors) information which is crucial for finding absolute motions at particular positions on the barge. For example, the absolute vertical motion at the bow at a given frequency of interest is the vector sum of the barge heave and the vertical motion due to the pitch rotation at that distance from the center of gravity (barge length/2). For simulation purposes a random vector of phases is used to model the waves. The response spectrum $S_{kk}(f_i)$ for the absolute motion in direction k at one position on the barge is then found from:

$$S_{kk}(f_i)=(^2/_T)[A_k^*(f_i)A_k(f_i)] \qquad (2)$$

where $A_k(f_i)$ is the (complex) absolute motion at frequency f_i, at a given point on the barge, in the longitudinal, lateral, or vertical direction (index k= 1, 2, or 3), * denotes the complex conjugate, and T (seconds) is the reciprocal of the frequency spacing used for the frequency vector where $\Delta f=(^1/_T)$.

It is well known that, for monochromatic motions at frequency f_i, the acceleration time series $a(t |f_i)$ is proportional to the displacement time series x(t) multiplied by the discrete (radian) frequency squared:

$$a(t |f_i)=(2\pi f_i)^2 x(t) \qquad (3)$$

This relationship was used to convert the displacement-based output from the SCORES program directly into acceleration-based values meaningful for this seasickness study (as described in the subsequent section). Specifically, the FORTRAN coding in SCORES was modified by multiplying the motion RAOs by $(2\pi f_i)^2$ according to Equation (3). This converted the (SCORES internal) displacement-based functions $A_k(f_i)$ into equivalent acceleration-based functions, and in turn into acceleration spectra via Equation (2) that were directly useful for this study.

A series of simulations were performed using the different barge configurations and incident seas previously described. Assuming a Gaussian probability distribution for the wave and acceleration time series (using moderate seas and linear RAOs), the following vertical acceleration spectral data were then extracted for each barge position shown in Figure 1:

- spectral peak,
- corresponding frequency, and
- root-mean-square (RMS) acceleration.

2

For instances where double peaks were comparable, the instantaneous frequency was used. The following standard equation was used to estimate the instantaneous frequency:

$$\omega = (a_1^2\omega_1 + a_2^2\omega_2)/(a_1^2 + a_2^2). \tag{4}$$

The following summarizes this analysis approach:

1. The logistics operation addressed in this study is the ferrying of cargo using a barge from a vessel to a floating pier at a site exposed to waves. A unidirectional wave spectrum corresponding to a mean Sea State 3 was used.

2. The condition chosen to represent this operation was the dynamics of a barge carrying one Abrams tank. A range of incident wave directions was used for generality. (Thus, the "return trip" of the barge without cargo excited by waves was not addressed.)

3. Seasickness was defined as proportional to the vertical acceleration of various module configurations.

4. Several different configurations for the lighterage barge were analyzed. For each case, the RMS acceleration and the instantaneous frequency were used to quantify the responses.

5. These responses were then compared to seasickness measures as defined in the next section.

Seasickness Criteria Literature Survey

A number of sources were studied in order to find a suitable relationship between RMS acceleration and discomfort. They varied from ASTM standards to ship specific guides. This section contains bibliographic information as well as a short description of each work and its usefulness in this study.

Baitis, A.E., Bennett, C.J., Meyers, W.G., Lee, W.T.; Seakeeping Criteria for 47-ft, 82-ft, and the 110-ft U.S. Coast Guard Cutters; CRDKNSWC-HD-1424-01; Carderock Division, NSWC, Bethesda, MD; November 1994.

> This document goes into significant detail about 3 particular vessels' seakeeping performance. This includes seasickness data, but it is specific only for the vessels presented. Since the 3 vessels were not similar to the barges used in the study, this report was used only for background.

Daidola, John C., Griffin, James J.; "Developments in the Design of Oceanographic Ships"; SNAME, *Transactions*, Vol. 94; 1986; pp. 121-158.

> This document presents some seasickness information in Figure 9 on page 131 (also present in ASTM F 1166-94), which was chosen as the best relationship between seasickness and RMS acceleration. This relationship

was the most complete as it was the only one which most thoroughly dealt with the proper range of frequencies with respect to RMS acceleration.

"Deck Motion can affect human performance"; Deepwater Production.

This source provided some information about work performance on steel ocean platforms (as well as tall buildings). The relationship provided by this paper was found to be inappropriate for this study.

Evaluation of Human Exposure to Whole-body Vibration - Parts 1, 2 & 3; ISO 2631; International Organization for Standardization; 1985.

This document discusses the varying levels of vibration that humans can experience in buildings and aboard ships. The figure on page 3 of ISO 2631/3 provides useful information, however, other sources provide a similar relationship with more detail. This standard was used only for background in the study.

Hutchinson, Brian; "Seakeeping Studies - A Status Report"; SNAME Transactions; 1990; pp. 263-318.

This document discusses in detail both the linear and nonlinear aspects of seakeeping problems. This article provides some insight regarding seasickness levels.

Marchaj, Czeslaw A.; Seaworthiness: The Forgotten Factor; International Marine Publishing Company, Camden, ME; 1986.

This book contains a significant section covering the effect of motion on crew performance. Figure 42 on page 75 was included in the analysis as one of the methods by which seasickness was evaluated.

Ship Vibration Design Guide; Ship Structure Committee; SSC-350; 1990.

This document is primarily concerned with shipboard vibration. It discusses in great detail the effects of the periodic forces generated by the propeller and machinery systems. It does not discuss the transient forces associated with rough seas. It was used as background.

Smith, T.C. & Thomas, W.L., III; A Survey and Comparison of Criteria for Naval Missions; DTRC/SHD-1312-01; David Taylor Research Center; October 1989.

This report lists overall dynamic criteria for various naval missions. It discusses the effects of various forces on humans and on equipment. No frequency dependence information is provided.

<u>Standard Practice for Human Engineering Design for Marine Systems, Equipment and Facilities</u>; ASTM F 1166-94; American Society for Testing and Materials; Philadelphia, PA; 1994.

> This standard contains the same graph as the Daidola, Griffin article on p 113 (Figure 98).

Vossers, Prof. Dr. Ir. G.; <u>Behavior of Ships in Waves</u>; The Technical Publishing Company H. Stam N.V., Haarlem, The Netherlands; 1962.

> This book is a thorough study of the fundamentals of ship behavior in waves. It includes some discussion of seasickness levels which is summarized in Figure 305 on page 255. This summary graph was one of the criteria used in analyzing the SCORES results.

The literature review showed that: (1) the problem of seasickness has been studied in the past but (2) no definitive conclusions were evident. For example, different criteria for quantifying seasickness were cited. One commonality was that the vertical component of acceleration was the major cause of seasickness. Therefore, this was the only barge response considered for this study. Of all these sources only <u>ASTM 1166-94</u> was ultimately used in evaluating the numerical results. This manual provides a measure called "Time for 10% sick". This measure was used by plotting the peak frequency and RMS acceleration for each deck position and incident direction of waves versus the standard (Figure 98 on page 113 in <u>ASTM 1166-94</u>) which is reproduced as Figure 2 in this report. The result indicates the amount of time that average people can be exposed to such wave conditions before 10% would develop motion sickness. This standard has been approved for use by any Department of Defense agency.

Study Results

The ASTM standard is based on a monochromatic/single frequency response. Therefore, some approximations are unavoidable when applying it to real world accelerations caused by multiharmonic ocean waves. For example, the SCORES-estimated spectra ranged from a narrow band (consistent with this monochromatic assumption) to a bimodal/wideband (which is definitely not monochromatic). To approximate this second situation, the instantaneous frequency was calculated and treated as the most representative monochromatic frequency of that acceleration response. In both cases the amplitude of motion is approximated adequately by the RMS value.

Several plots were developed to help identify behavior trends for the various configurations. The attached figures use the following abbreviations to describe each case:

Key	Longitudinal Number of Modules	Length (ft)	Transverse Number of Modules	Beam (ft)	Height (ft)	Water Depth (ft)
L80D100	2	80	1	24	8	100
L120D12	3	120	1	24	8	12
L120D100	3	120	1	24	8	100
L160D100	4	160	1	24	8	100
L120W48	3	120	2	48	8	100
L120H7	3	120	1	24	7	100

Points 2 and 3 (see Figure 1) were considered the most significant to examine as they represented the points which would experience the greatest and least RMS acceleration, respectively. Point 2 is at the starboard bow of the barge, furthest from the center of gravity. Therefore, it would generally experience the greatest acceleration and, subsequently, the highest seasickness potential. Point 3 is at the center of the barge, just above the center of gravity. This point is least susceptible to the effects of rotation and, thus, experiences the least acceleration and therefore the lowest seasickness potential. Since the center of the barge deck is the place where the seasickness potential will be lowest, it would be the best place to go in exceptionally rough weather in order to minimize the crew's discomfort. Figures 3 and 4 show the seasickness levels for these points at all wave angles for all barge configurations.

Three final points are given that will also influence the ability of a crew to effectively operate in a dynamic environment. First, it is noted that all seasickness measures assume continuous motion. However, this may not be true in this application because the barge will spend some finite time in the lee of the cargo vessel and/or at the pier while loading and unloading cargo. While the barge will still be affected by the waves while loading and unloading, this does provide an opportunity for personnel to disembark and minimize their exposure to the waves. *This would therefore act to increase the time available for working in that wave environment.* Secondly, this study assumed a mean Sea State 3 wave environment. The mathematical representation of random seas as a narrowband, unidirectional spectrum is admittedly one idealized definition of a wide range of a very diverse wave conditions. For example, breaking waves (and the associated impulsive impact motions of a barge) and independent long period swell from a different incident direction were not considered. Also, spectra such as the Bretschneider spectrum are based on fully-developed seas; seas produced by quick-moving storm fronts can produce seas with comparable wave amplitudes but very different frequency content. So while the reader is cautioned that these phenomena can all produce significant variations in the wave excitation and hence the barge responses, the standard industry approach of using idealized wave spectra was used in this study. Third, the seasickness limits were not explored for Sea States lower than 3.

Observations from this parametric study are presented next.

General Observation - The contrast between Figures 3 and 4 is striking. Generally speaking, Figure 3 shows that a crew can work at the starboard bow for only <u>one hour</u> regardless of the barge configuration and wave heading as measured by the "Time for 10% sick" standard. This span seems very restrictive to real-world operations. However, Figure 4 shows that the effective work time increases dramatically to generally <u>seven hours</u> for all barge configurations and most headings if the crew moves to the center of the deck. *This is a dramatic difference due simply to position on the deck.*

Furthermore, it is possible to examine the relative effect of various barge configuration parameters on the seasickness potential: length, beam, height, water depth, and wave angle. Each will be discussed briefly. When improved performance is indicated, this corresponds to an increase in the "Time for 10% sick".

Length Effects - Increasing the barge length had only minor effect on the seasickness levels. In examining the difference between the 120-ft long vs. the 160-ft long barges, both operating in 100-ft deep water, the "Time for 10% sick" did not exhibit any definite increase corresponding to the increase in length.

For attachment point 2 as shown in Figure 3, there was a slight increase in the "Time for 10% sick" which depended upon the wave angle. For example, for a wave angle of 22.5°, the "Time for 10% sick" was 0.75 hours for the 120-ft barge, and 1 hour for the 160-ft barge. However, for most of the curve, the two configurations displayed almost identical results.

For attachment point 3 at the deck center, there was no significant increase in the "Time for 10% sick" corresponding to an increase in length. For example, for a wave angle of 0°, the allowable time increased from 7 to 8 hours as the barge length increased from 120 to 160-ft. But, at a wave angle of 45°, the allowable time decreased from 8 to 7 hours as the barge length increased from 120 to 160-ft. This is most likely within the margin of error of the evaluation process.

Beam Effects – As expected, doubling the barge beam using two modules proved to have the most effect when examining the 90° wave angle. Consider attachment point 3 shown in Figure 3. The doubled barge showed a "Time for 10% sick" that was 8 hours or higher for *all* wave angles. Compare this to the single width 120-foot long barge, where the "Time for 10% sick" was 7 hours at wave angles of 0° and 22.5°, 8 hours at wave angles of 45° and 67.5°, but only *two* hours at a 90° wave angle. At the other attachment points, this double width barge performed similarly to its single width counterpart for wave angles of less than 90°. Only for attachment points 1 and 3 were there significant increases (2 hours to 8 hours) in the "Time for 10% sick" at a 90° wave angle.

Height Effects - Reducing the module height by 1 foot, which in effect lowered the center of gravity closer to the waterplane, reduced the effective time for working in most cases. The overall motions were expected to decrease due to the reduced moment arm, but instead they increased slightly. This is attributed to the reduction in the barge mass (associated with the 7 ft rather than 8 ft height) which in turn increased the translational motions. For example, in comparing the accelerations for 120-ft barges, the baseline 8-ft high configuration performed the same or better at all points and wave angles. As shown in Figure 3, at point 3 at a wave angle of 45°, the "Time for 10% sick" increased from 4 to 8 hours as the barge height increased, while at point 2 the "Time for 10% sick" was 45 minutes for both barge heights.

Water Depth Effects - When operating in shallower water (12-ft vs. 100-ft), the barge performance was generally better. At wave angles of 22.5, 45 and 90°, the "Time for 10% sick" was the same or higher at all attachment points when the water depth was only 12-ft. For example, at point 3 at a wave angle of 22.5°, the "Time for 10% sick" was 8 hours versus 7 hours when comparing 12-ft to 100-ft water depths, respectively. In two cases the barge in 100-ft deep water performed better than the barge in 12-ft deep water: at point 1 at a 0° wave angle (3 hours with 100-ft depth versus 2 hours with 12-ft depth) and at point 4 at a 67.5° wave angle (4 hours with 100-ft depth versus 2 hours with 12-ft depth).

Wave Angle Effects - The effect of wave angle is dependent upon which point is being examined. The following table presents the wave angles at which the best overall performance was observed for each point for any barge configuration.

Attachment Point	Optimum Wave Angle (°)
1	67.5
2	0
3	67.5
4	0

Summary & Conclusions

This study was undertaken to examine the behavior of modular barges in a Sea State 3 wave environment. With the results of this study, it was possible to determine the relative levels of seasickness that a crew might experience on such a barge. In addition, by varying certain factors in the study, it was hoped that some basic guidelines for countering the detrimental effects of motion sickness could be developed.

The following primary conclusions were reached for the various barge configurations and incident wave directions:

1. This study has found that seasickness will have an effect on a crew regardless of the barge size. Depending on where they operate on the barge deck, a crew can operate for between 1 and 8⁺ hours according to the seasickness criteria.

2. Not surprisingly, the center of the barge consistently gave the highest "Time for 10% sick" and would be calmest place for the crew in cases of rough weather. Moving to the center of the barge (point 3) from a corner (point 2) resulted in a 5-½ to 7 hour increase in the "Time for 10% sick" ranging.

3. Increasing the length of the barge by assembling multiple modules has no significant effect on the seakeeping characteristics for all incident wave directions (approximate increase of "Time for 10% sick" by 1 hour (from 7 to 8 hours) occurred at a few wave angles, but not all).

4. Increasing the beam of the barge by assembling multiple modules does improve the seakeeping for beam seas by increasing the "Time for 10% sick" at points 1 and 3 from 2 to 8 hours.

Reference

(1) Kaplan, P., Users Manual for SCORES II Program - NCEL Version, Hydromechanics Report 81-31, July, 1981.
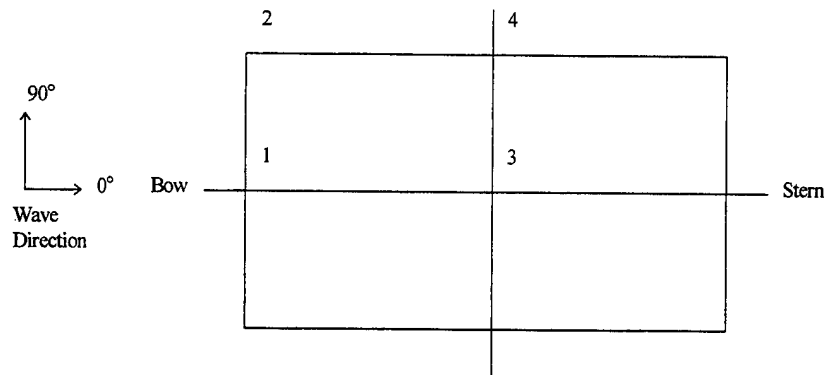
2 4

90°

1 3

0° Bow ——— Stern

Wave
Direction

Figure 1 - Point Location Diagram

M/SEC² g

10.0 — 1.00
9.0
8.0 — 0.800
7.0
6.0 — 0.630
5.0 — 0.500
4.0 — 0.400

3.0 — 0.315

— 0.250

rms ACCELERATION aₓ

2.0 — 0.200   10 PERCENT SICK

— 0.160

— 0.125   1/2
HOUR

1.0 — 0.100
0.9
0.8 — 0.080   1
0.7   HOUR
0.6 — 0.063   2
0.5 — 0.050   HOURS

0.4 — 0.040   8   4
HOURS   HOURS

0.3 — 0.0315

— 0.025

0.2 — 0.020

— 0.016

— 0.0125

0.1

0.05 0.08 0.125 0.20 0.315 0.50 0.80
0.063 0.10 0.16 0.25 0.40 0 63 1.0

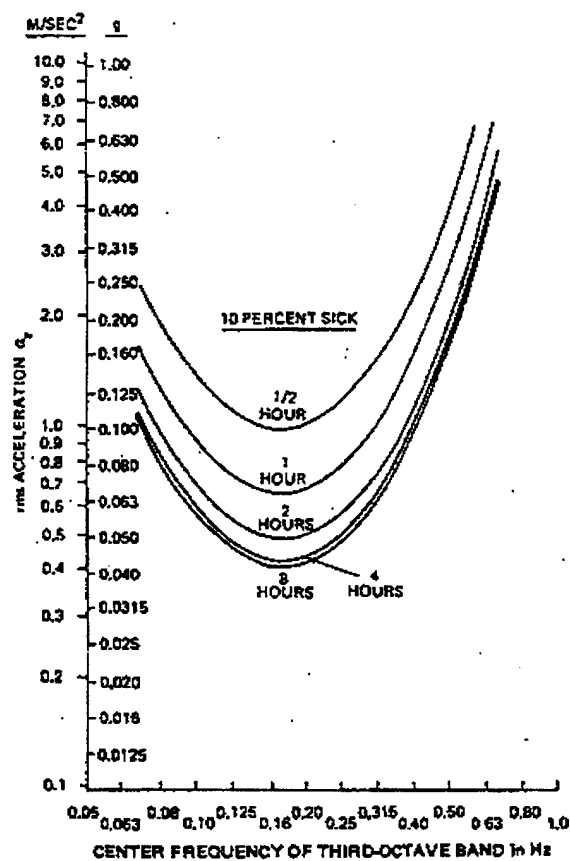CENTER FREQUENCY OF THIRD-OCTAVE BAND in Hz

**Figure 2– The 90% Motion Sickness Protection Limits for Human
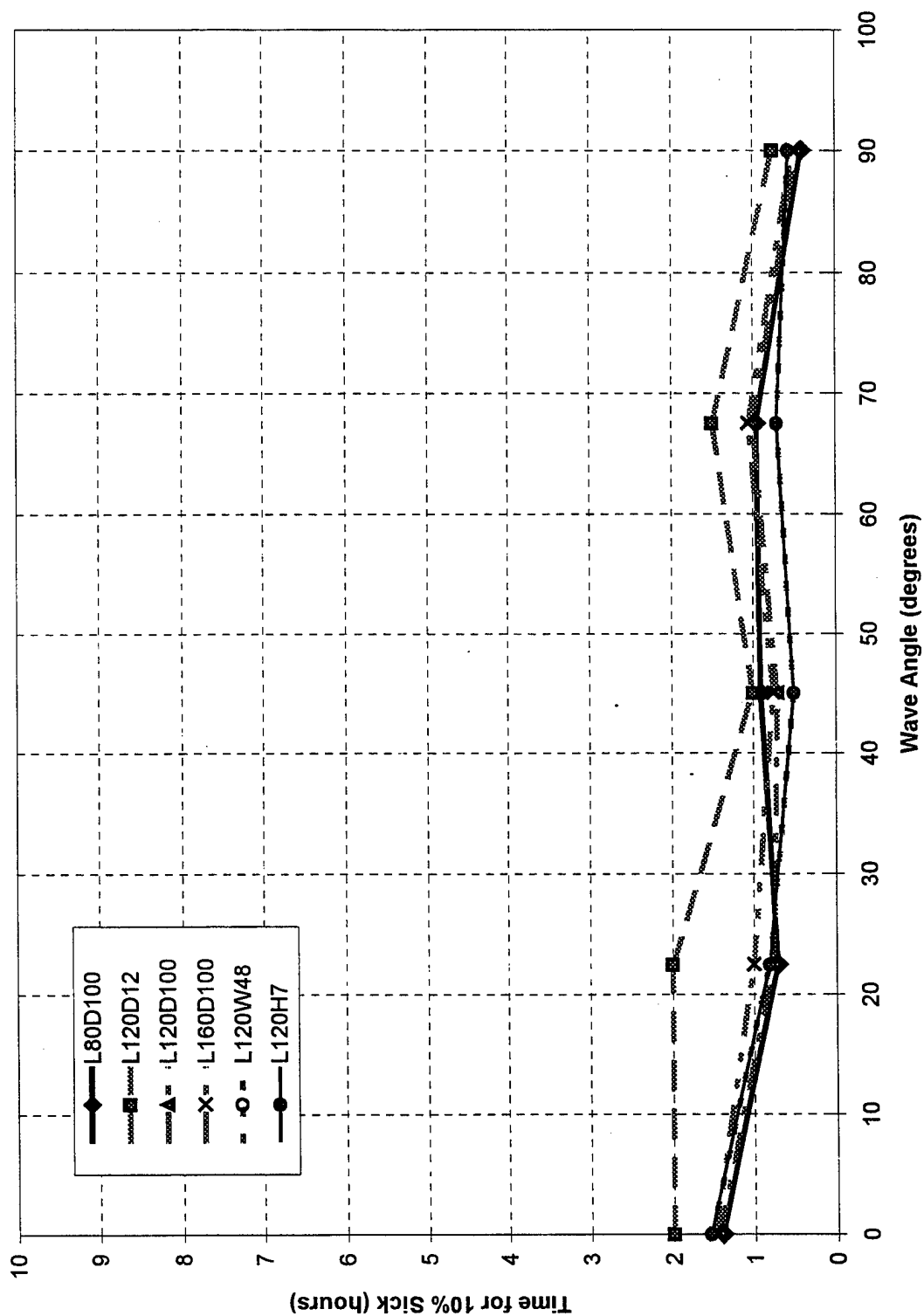Exposure to Very Low Frequency Vibration (ASTM F1166-94)**

Figure 3- Attachment Point 2

Figure 4 - Attachment Point 3